Wide Field Imaging II: Mosaicing

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Tenth Summer Synthesis Imaging Workshop
University of New Mexico, June 13-20, 2006

Contents

- Mosaicing: required when a source is BIG.
- How mosaicing works: Effective (*uv*) coverage
- Mosaicing algorithms
- Preparing mosaic observations

Mosaicing → Overlapping Fields

Surveys for point sources
Serpens 3 mm continuum:

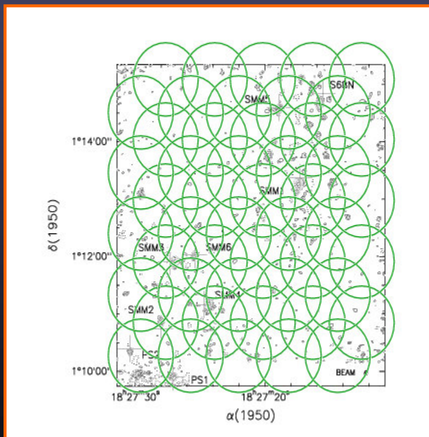
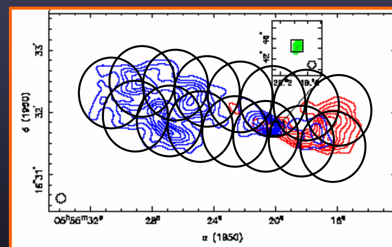


Image extended emission
G192.16 CO(J=1-0) outflow:

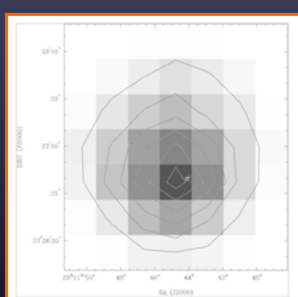


Mosaicing → Adding Zero Spacing Flux

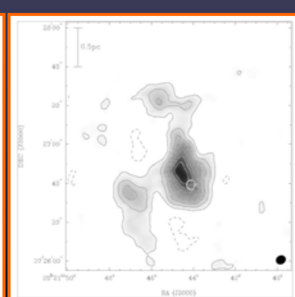
BIMA + 12m = Combined Interferometric Mosaic

G75.78 star forming region in CO(J=1-0)

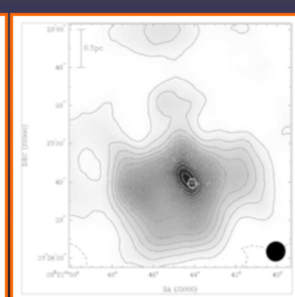
12m



BIMA



12m + BIMA



How Big is "BIG"?

- Bigger than the Primary Beam: λ**/D** Full Width Half Max
- Bigger than what the shortest baseline can measure: Largest angular scale in arcsec, $\theta_{LAS} = 91{,}000/B_{short}$
  - If adequate number of baselines, VLA shortest baselines can recover:
    80% flux on 1/5 λ**/D** Gaussian;
    50% on 1/3 λ**/D** Gaussian
  - CLEAN can do well on a 1/2 λ**/D** Gaussian
  - MEM can still do well on a high SNR 1/2 λ**/D** Gaussian

➔ Lack of short baselines often become a problem before source structure is larger than the primary beam:

Mosaicing is almost always about Total Power!

θ_{LAS}

- θ_{LAS} is a function of wavelength:
  - VLA at 21 cm (L band): 15'
  - VLA at 3.6 cm (X band): 3'
  - VLA at 0.7 cm (Q band): 40"
  - OVRO at 2.7 mm (115 GHz): 20"
  - ALMA at 1 mm (230 GHz): 13"
  - ALMA at 0.4 mm (690 GHz): 4"

➔ Mosaicing becomes more critical at short wavelengths.

An Example

- Assume a model brightness distribution: $I(x)$
- Simulated visibilities are given by a Fourier transform:

Primary beam ↓

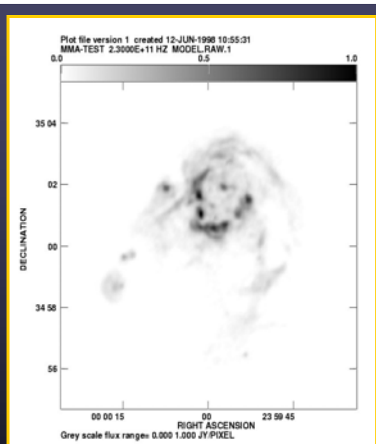
$$V(u) = \iint (A(x - x_p)\, I(x))\, e^{-2\pi i (u \cdot x)}\, dx$$

- Estimate of brightness distribution at a single pointing is:

$$I^{recon}(x) \,/\, A(x - x_p)$$

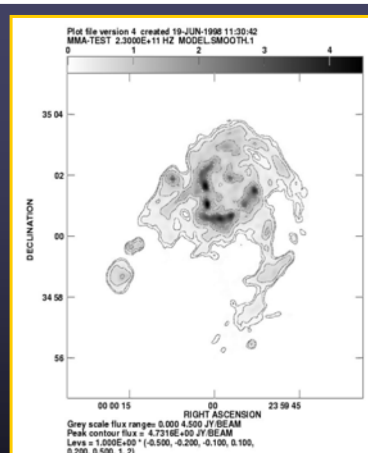
- Need more pointings!

An Example: Simulated Data



$I(x)$

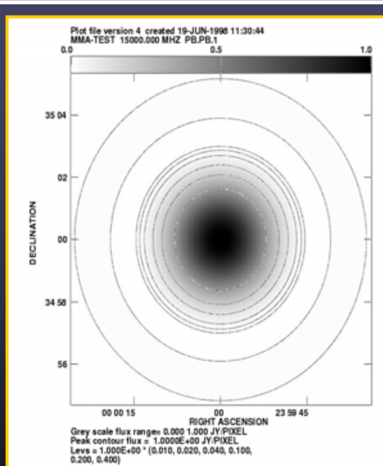
Raw model brightness distribution



$I(x) * B_G(x)$

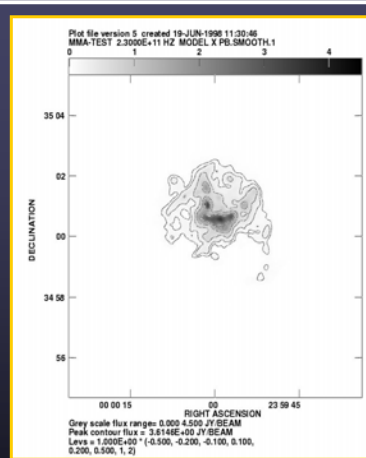
Image smoothed with 6” Gaussian
(VLA D config. resolution at 15 GHz)

An Example: Simulated Data



$A(x - x_p)$

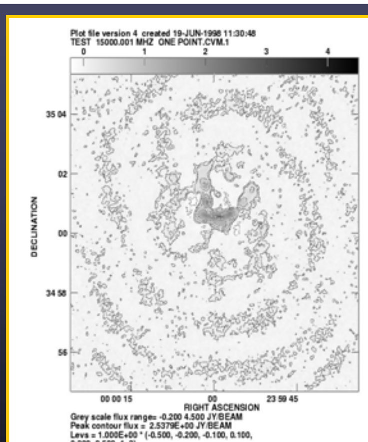
Primary beam used for simulations



$A(x - x_p)\ I(x) * B_G(x)$

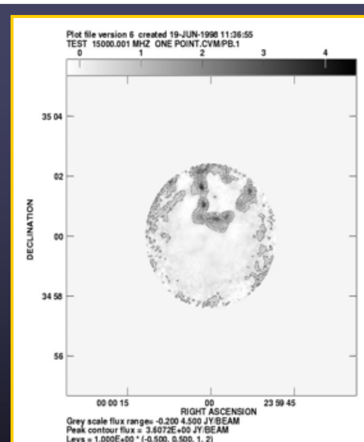
Model multiplied by primary beam & smoothed with 6” Gaussian. Best we can hope to reconstruct from single pointing.

An Example: Reconstructed Simulated Data



$I^{recon}(x)$

Visibilities constructed with thermal Gaussian noise. Image Fourier transformed & deconvolved with MEM



$I^{recon}(x) / A(x - x_p)$

Primary beam-corrected image. Blanked for beam response < 10% peak. Need to Mosaic!

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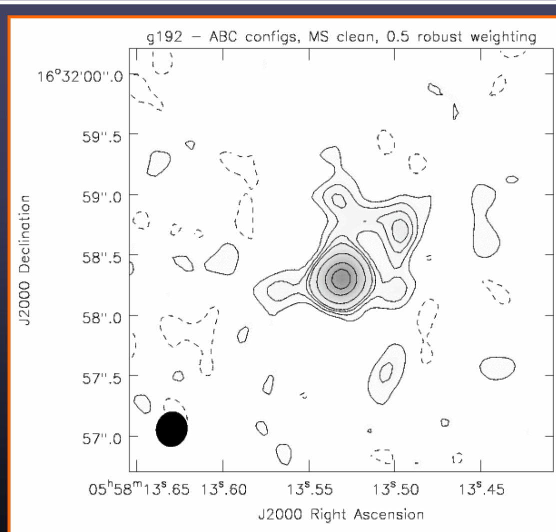
Another Example: Dealing with Archive Data!

How to deal with Archive data taken with different pointing centers. Single dish data not needed.

Example VLA data: B & C configuration data taken with same pointing & correlator setup. A configuration data taken at slightly different frequency and offset pointing center of ~1.0"

Final image created with mosaic gridding, multi-frequency synthesis, multi-scale CLEAN deconvolution.



Shepherd et al. in prep.

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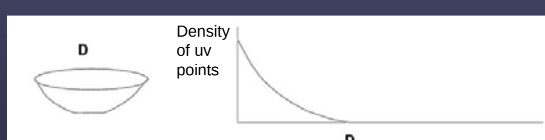
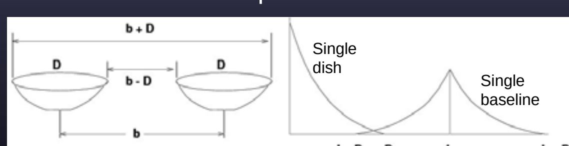
Effective *uv* coverage – How Mosaicing Works

- Single dish: scan across source, Fourier transform image to get information out to dish diameter, ***D:***



- Ekers & Rots (1979): One visibility = linear combination of visibilities obtained from patches on each antenna:

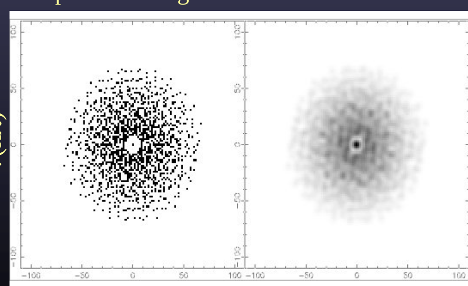


- But, can't solve for N unknowns (Fourier information on many points between ***b-D*** & ***b+D***) with only one piece of data (a single visibility measurement). Need more data!

How Mosaicing Works

- Ekers & Rots obtained information between spacings ***b-D*** & ***b+D*** by scanning the interferometer over the source and Fourier transforming the single baseline visibility with respect to the pointing position. So, changing the pointing position on the sky is equivalent to introducing a phase gradient in the ***uv*** plane. This effectively smooths out the sampling distribution in the ***uv*** plane:

Snapshot coverage   Effective mosaic coverage



v(kλ)

u(kλ)   ***u***(kλ)

An Example: Simulated Mosaic

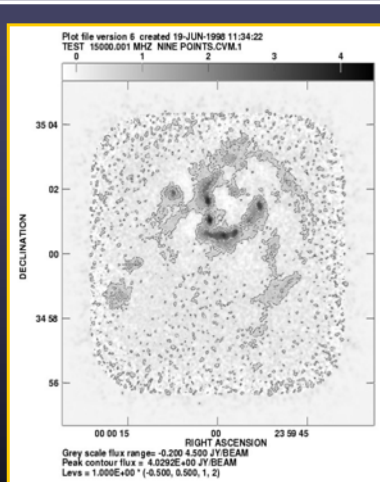
- Try 9 pointings on simulated data. We could deconvolve each field separately and knit together in a linear mosaic using:

$$I_{mos}(x) = \frac{\Sigma_p A(x - x_p)\, I_p(x)}{\Sigma_p A^2(x - x_p)}$$

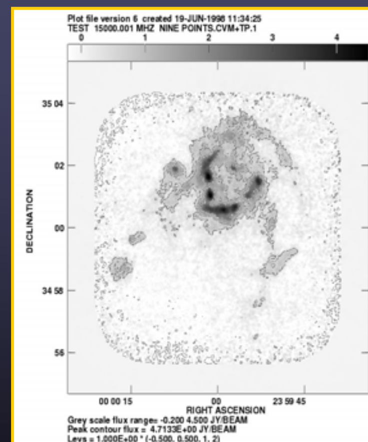
- But, Cornwell (1985) showed that one can get much better results by using all the data together to make a single image through joint deconvolution.

In practice, if spacings close to the dish diameter can be measured (***b ~ D***), then the "effective" Fourier plane coverage in a mosaic allows us to recover spacings up to about ½ a dish diameter. Still need Total Power.

An Example: Reconstructed Simulated Data



Nine VLA pointings deconvolved via a non-linear mosaic algorithm (AIPS VTESS). No total power included.

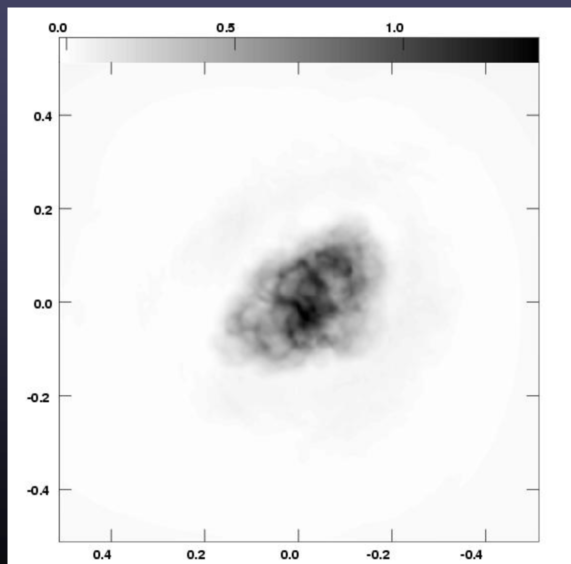


Same mosaic with total power added.

Interferometers & Single Dishes

Array	Number Ants	Diameter (m)	B_{short} (m)	**Single Dish**	Diameter (m)
VLA	27	25	35	GBT or VLBA	100 25
ATCA	6	22	24	Parks	64
OVRO	6	10.4	15	IRAM or GBT	30 100
BIMA	10	6.1	7	12m, GBT or IRAM	12, 100 30
PdBI	6	15	24	IRAM	30

Mosaics in Practice



Crab Nebula at 8.4 GHz. (Cornwell, Holdaway, & Uson 1993).

VLA + Total power from a VLBA antenna

Non-Linear Joint Deconvolution

- Find dirty image consistent with ALL data. Optimize global χ^2:

$$\chi^2 = \sum_{i,p} \frac{|V(u_i,x_p) - \hat{V}(u_i,x_p)|^2}{\sigma^2(u_i,x_p)}$$

The gradient of χ^2 w.r.t. the model image tells us how to change the model so χ^2 is reduced:

Dirty image — Point spread fctn — Primary beam — Global model image

$$\nabla\chi^2(x) = -2\Sigma_p A(x - x_p)\ \{I_{p,}(x) - B_p(x) * [A(x - x_p)\ I_{(x)}]\}$$

Residual image for pointing p

- Like a mosaic of the residual images; use to steer optimization engine like non-linear deconvolver MEM. **AIPS: vtess & utess.**

Joint Deconvolution (Sault et al. 1996)

- Dirty images from each pointing are linearly mosaiced. An image-plane weighting function is constructed that results in constant thermal noise across the image (source structure at the edge of the sensitivity pattern is not imaged at full flux).
- Dirty beams stored in a cube. $\nabla\chi^2(x)$ residual image is formed and used in MEM and CLEAN-based deconvolution algorithms.
- Final images restored using model intensity & residuals.

MIRIAD: invert; mosmem or mossdi; restore.

Linear Mosaic of Dirty Images with Subsequent Joint Deconvolution

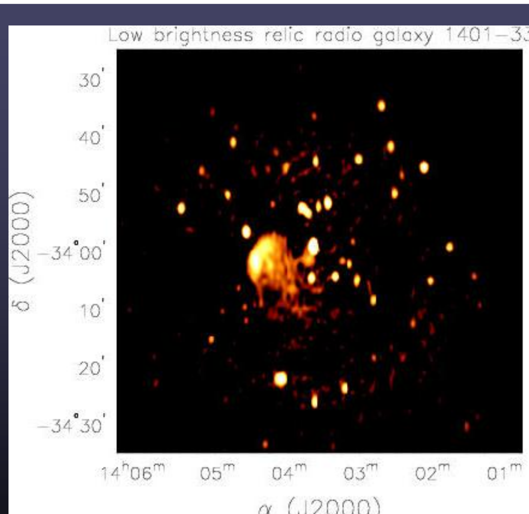
- Limited dynamic range (few hundred to one) due to position dependent PSF.   AIPS: ltess
- This can be fixed by splitting the deconvolution into major and minor cycles. Then subtracting the believable deconvolved emission from the data and re-mosaicing the residual visibilities. AIPS++: imager

Linear Mosaic + Joint Deconvolution with Major/Minor Cycles

- Dirty images from each pointing are linearly mosaiced. AIPS++: imager
- Approximate point spread function is created common to all pointings. *Assures uniform PSF across mosaic.*
- Image deconvolved until approx. PSF differs from true PSF for each pointing by specified amount. Model is subtracted from the observed data (in visibility or image plane) to get residual image. Iterations continue until peak residual is less than cutoff level.
- AIPS++ deconvolution algorithms in **imager**: mem, clean, msclean. msclean simultaneously cleans N different component sizes to recover compact & extended structure.

Challenges

- Low declination source
- Bright point sources
- Faint, extended emission



Relic radio galaxy 1401-33.
(Goss et al. 2002)

ATCA L band mosaic, 11 fields, deconvolved with AIPS++, multi-scale clean. No total power included.

Adding in Total Power

Total power obtained from a single dish telescope can be:

- Added in *uv* plane (MIRIAD: invert). Single dish image must be Fourier transformed to create simulated *uv* coverage.
  Example: MIRIAD: HI in the SMC.
- "Feathered" with an interferometer image after both images are made (AIPS++: image.feather, MIRIAD: immerge). IF there is sufficient *uv* overlap between interferometer and single dish data (VLA+GBT, OVRO/BIMA+IRAM, ATCA+Parkes).
  Example: MIRIAD: Galactic center CS(2-1)
- Used as a starting model in deconvolution (AIPS++: imager 'makemodelfromsd' with subsequent clean). Model created from a single dish image is used as an initial model during deconvolution. The model is improved where *uv* coverage overlaps.
  Example: AIPS++: Orion

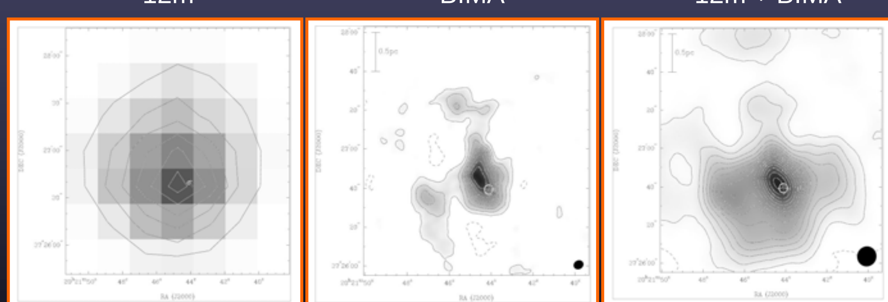
Caution: if the single dish pointing accuracy is poor, then the combined image can be significantly degraded. The only existing single dish that can produce images of similar quality to what an interferometer can produce is the GBT.

MIRIAD: *uv* Plane Combination

BIMA + 12m = Combined Interferometric Mosaic

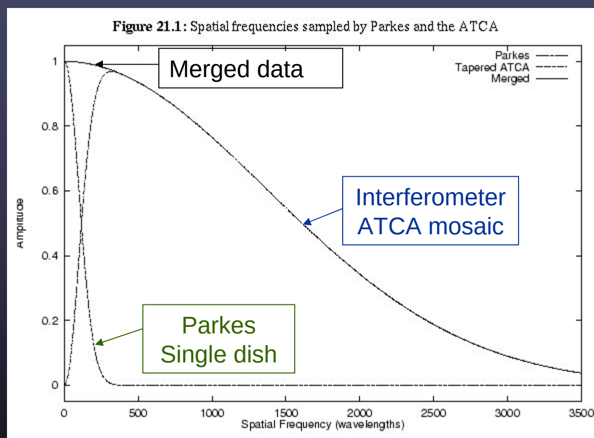
G75.78 star forming region in CO(J=1-0)

12m | BIMA | 12m + BIMA



Resolution in final image is a compromise between interferometer and single dish images. Loose information on compact structure and the relation to extended emission.

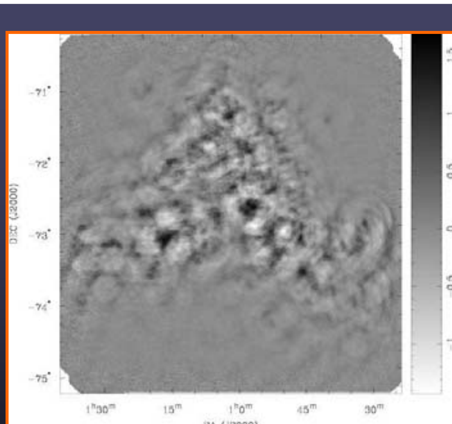
Linear Image Feathering



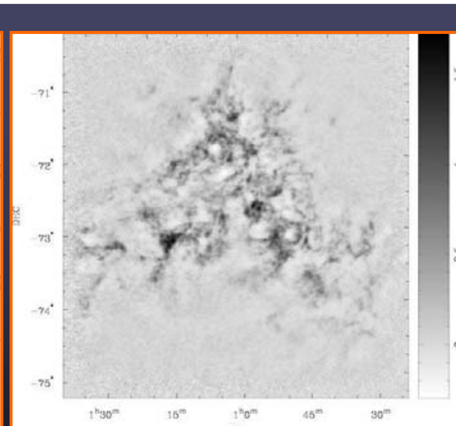
If there is significant overlap in ***uv*** coverage: images can be "feathered" together in the Fourier plane.

MIRIAD immerge & AIPS++ imager.feather taper low spatial frequencies of mosaic interferometer data to increase resolution while preserving flux. Can taper interferometer data to compensate.

MIRIAD Feathered Mosaic of the SMC

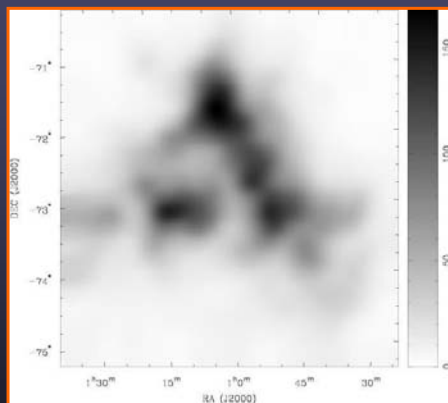


ATCA observations of HI in the SMC. Dirty mosaic, interferometer only.

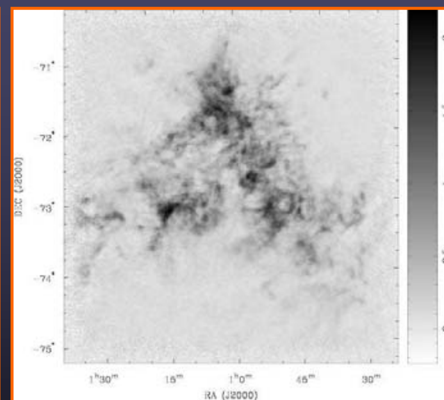


Deconvolved mosaic, interferometer only. Stanimirovic et al. (1999).

MIRIAD Feathered Mosaic of the SMC

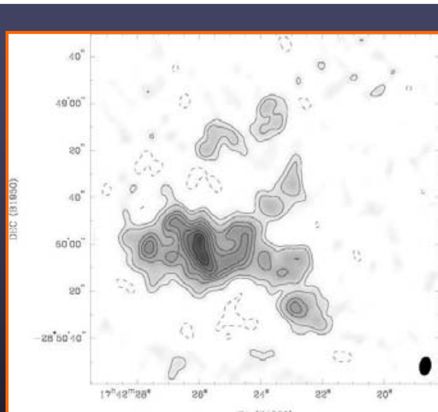


Total power image from Parkes.

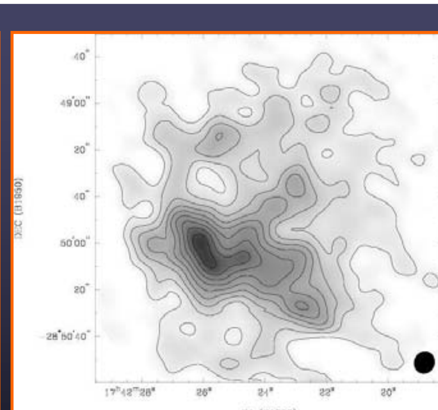


Interferometer plus single dish feathered together (**immerge**). Stanimirovic et al. (1999).

MIRIAD Feather: CS(2-1) Near the Galactic Center



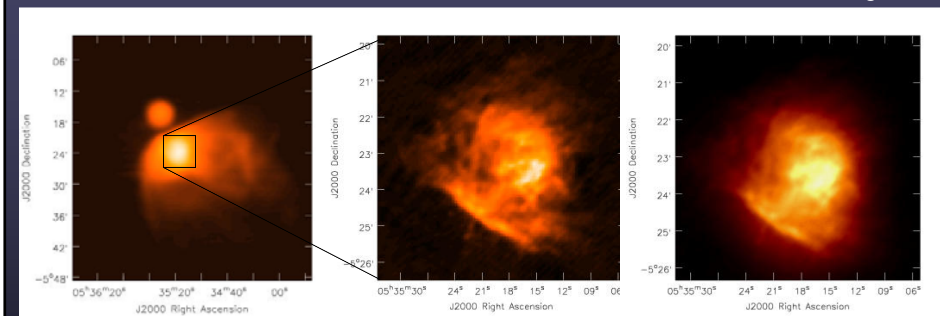
OVRO mosaic, 4 fields.
Deconvolved with MEM.



OVRO+IRAM 30m mosaic using MIRIAD: immerge feather algorithm. (Lang et al. 2001).

Ionized Gas (8.4 GHz) in the Orion Nebula

Feathered image



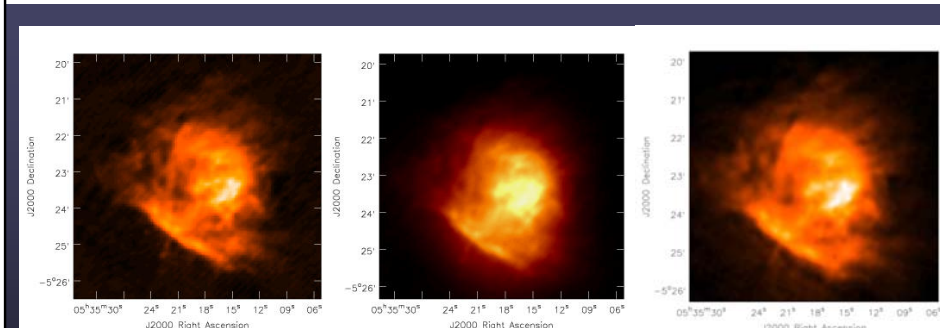
GBT On-the-fly map of the large field, (AIPS++). 90” resolution.

VLA mosaic of central region, 9 fields. Deconvolved with MEM in AIPS++. 8.4” resolution.

GBT+VLA mosaic using AIPS++ image.feather. (Shepherd, Maddalena, McMullin, 2002).

Dissimilar resolution is a problem.

Ionized Gas (8.4 GHz) in the Orion Nebula



VLA mosaic of central region, 9 fields. Deconvolved with MEM in AIPS++. 8.4” resolution.

Feathered GBT+VLA mosaic using AIPS++.

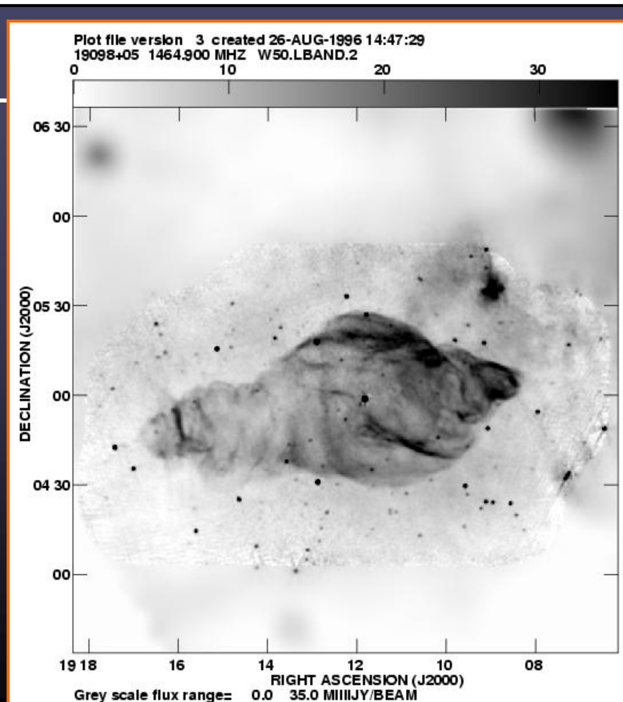
Image looks pretty but fidelity (quality) is low due to disparate 90” and 8.4” resolutions.

GBT+VLA mosaic – GBT image input as a model and then deconvolved with multi-scale CLEAN.

Final image fidelity significantly better.

Good Mosaic Practice

- Point in the right place on the sky.
- Nyquist sample the sky: pointing separation $\leq \lambda/2D$
- Observe extra pointings in a guard band around source.
- If extended structure exists, get total power information. Have good ***uv*** overlap between single dish and interferometer (big single dish w/ good pointing/low sidelobes & short baselines).
- Observe short integrations of all pointing centers, repeat mosaic cycle to get good ***uv*** coverage and calibration until desired integration time is achieved.
- For VLA: Either specify each pointing center as a different source or use //OF (offset) cards to minimize set up time.



W50 Supernova Remnant

(Dubner et al. 1998)